EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 467

Control of field quality for the production of the main LHC dipoles

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Abstract

We review the warm magnetic measurements of the first four main dipole prototypes (8 apertures) and their agreement with nominal design. We then estimate the order of magnitude of the corrections that may be needed to re-center the low-order normal harmonics around the nominal values for the forthcoming series production. Correction strategies that provide the minumum impact on production schedule and costs are analysed. For the case of b_3 and b_5 two possibilities are considered: a variation of the shims to optimize the azimuthal length of the two coil layers, and a variation of the copper wedges of the inner layer, leaving unchanged the azimuthal coil size. For optimizing b_2 and b_4, we consider modifications of the shape of the ferromagnetic insert, that is placed between the collars and the yoke. Comparison between measurements and simulations of the implemented insert modifications are given and a final design is proposed. Intrinsic limits to the control of field quality during the production are discussed.

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Geneva, 28 March 2001

1 Introduction

The pre-series production of the main LHC dipoles has been recently started [1]. In this paper we analyse the magnetic measurements at room temperature relative to four dipole prototypes. Checks againsts nominal values and targets for the beam dynamics are given.

We first analyse the data relative to the collared coils; these values are relevant for studying the odd normal multipoles, since the effect of the iron yoke is rather reproducible and in agreement with simulations [2]. We trace back the origin of an offset between the nominal values and the measured ones, and we propose two correction strategies to re-center and control the production.

We then analyse the assembled cold mass data to study the even normal multipoles. In order to correct the b_2 and b_4 observed in the prototypes, we propose a corrective action based on the modification of the ferromagnetic insert placed between the collars and the iron yoke. A special prototype has been built to test the proposed solutions: we discuss the agreement of simulations with experimental measurements and an insert design for the series production.

All the analysed correction strategies are aimed at minimizing the impact on the time schedule and costs. The approach is based on evaluating sensitivity tables that provide the effect of these corrective actions on field quality. Optimization of even multipoles through insert shaping has been already implemented.

2 Fine tuning of odd multipoles

2.1 Warm measurements of collared coils

In Table 1 we give the warm magnetic measurements carried out on the collared coils of the first four prototypes made with stainless steel collars: MBP2N2, MBP2O1, MBP2O2 and MBP2A2. Data of the first prototype with aluminium collars MBP2N1 are not considered, due to the different structure and materials. Averages along the straight part (first and last measurements are discarded because of end effects, 18 positions along the axis are kept) are given in the usual units of 10^{-4} at a reference radius of 17 mm. Conventions for aperture numbering and reference systems are given in [3]. Magnetic measurements are taken at low current (12 A) and at 300 K.

Table 1: Field-shape harmonics measured at room temperature of the first four prototypes, collared coils, straight part, in units 10^{-4} of dipole field at 17 mm

	MBP2N2		MBP2O1		MBP2O2		MBP2A2	
	Ap. 1	Ap. 2	Ap. 1	Ap. 2	Ap. 1	Ap. 2	Ap. 1	Ap. 2
b_3	3.8	2.3	-1.1	-3.0	6.3	5.3	-1.9	-1.7
b_5	-0.16	0.01	0.37	0.27	0.85	0.45	1.52	1.10
b_7	0.79	0.85	0.70	0.66	1.01	0.99	0.61	0.52
b_9	0.27	0.27	0.30	0.31	0.34	0.30	0.45	0.44
b_{11}	0.75	0.75	0.76	0.76	0.78	0.78	0.76	0.77

2.1.1 Systematic part

Experimental results for the averages are given in Table 2, second column. The harmonics expected in the collared coils with the nominal geometry are given in the

Table 2: Averages odd multipoles in the collared coils of the first four prototypes: measurements at 300 K, successive post-processing of measurements (A, B and C), and nominal values. A: measurements minus the effect of non-nominal shims. B: A minus the effect of coil deformations. C: B minus the effect of the magnetic permeability of the collars.

	Measur.	A	B	C	Nominal
b_3	1.2	1.5	4.7	5.9	3.9
b_5	0.55	0.41	-0.46	-0.80	-1.02
b_7	0.76	0.83	0.81	1.03	0.73
b_9	0.34	0.31	0.31	0.31	0.12
b_{11}	0.76	0.76	0.76	0.76	0.70

last column of the same table. A non-zero value of the sextupole and decapole components (around +4 and -1 units respectively) was originally put in the nominal design to partially compensate at injection the contribution of the persistent currents [4]. These nominal values take into account the geometry of the current distribution, but neglect the collar deformation due to prestress and the magnetic permeability of the collar. Moreover, the collared coil components are obviously assumed with nominal dimensions. The four prototypes feature in average a discrepancy of -2.7 units for the sextupole and +1.5 units of decapole with respect to the nominal design (difference between the second column and the last column of Table 2). In the following, we try to trace back the origin of this discrepancy. On the other hand, higher order multipoles show a better agreement with the design: the discrepancy is much less than half a unit from b_7 onward. This is an expected feature, since any displacement of the current lines affects less the higher orders than the low ones, according to a power series decrease given by the Biot-Savart law (see Ref. [5]). Therefore, high order multipoles are much easier to control than the low order ones.

The four prototypes have been built with shims (see Figure 1) different from the nominal ones, in order to optimize the azimuthal prestress that is imposed to the coil during manufacturing. Different shim thicknesses (see Table 3) have therefore given rise to different azimuthal coil lengths, and to a variation of the odd multipoles. The sensitivity of the multipoles on the azimuthal coil length is given in Appendix A, where a model without coil deformations is considered. In Table 2, third column (A), we subtract from the measured data the multipole variation due to shims different from the nominal ones according to our sensitivity estimate.

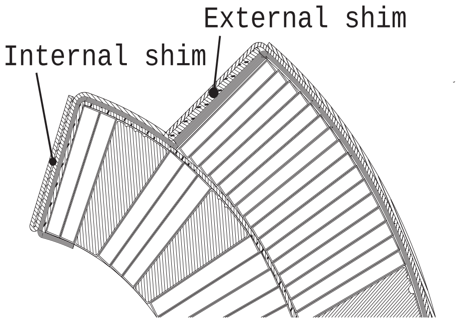

Figure 1: Cross-section of the LHC dipole coil, magnified view of the coil poles and shims

Table 3: Shim dimensions and azimuthal prestress measured in the collared coils at 300 K for the first four prototypes

	N2	O1	O2	A2	Nominal
Shims (mm)					
Internal	0.43	0.32	0.47	0.20	0.40
External	1.12	0.98	1.09	1.00	1.00
Prestress (MPa)					
Internal	62	51	55	50	60-90
External	77	55	64	52	60-90

Another contribution is given by the deformation of the coils. The azimuthal prestress imposed on the coil deforms the cavity of the collars and therefore modifies the coil shape and its multipolar content. The deformation is relevant at room temperature, where the azimuthal prestress in the collared coils is of the order of 50-75 MPa (see the data for the four prototypes in Table 3) [1)]. Due to the different thermal contraction coefficients of the coil and of the collars, one has a very strong prestress loss at 1.9 K, i.e. from 50-75 MPa to 20-30 MPa [6]. The impact of a given azimuthal prestress on the multipolar content is estimated in Appendix B through a finite element code [7] and a magnetostatic code [8]. In Table 2, fourth column (B), we subtract from experimental data both the contribution due to non-nominal shims, and to the collar deformation according to our estimates.

Another effect is due to the magnetic permeability of the stainless steel collars. An estimate of the influence of this parameter on field quality is given in Appendix C. The magnetic permeability at 1.9 K in the stainless steel used for the prototypes ranges from 1.0020 to 1.0035 [9]. At room temperature, we assume that all the prototypes were built with collars featuring the same magnetic permeability of 1.0020. In Table 2, fifth column (C), we subtract from experimental data the contribution of different shims, of the coil deformation, and of the magnetic permeability. The estimate (C) agrees with the nominal design, within two sigma of the distribution (see next paragraph).

Data from Table 2 show that the discrepancy between nominal design and measured values is mainly due to the collar deformation (-3.2 units of b_3 and +0.9 of b_5) and to the magnetic permeability of the collars (-1.2 units of b_3 and +0.35 of b_5). The shims do not give a relevant contribution since, in average, they have been chosen close to the nominal ones.

2.1.2 Random part

In Table 4 we carry out the analysis of the sigmas of the multipoles. Experimental data relative to the four analysed prototypes are analysed in the following way. We first consider the variation of multipoles from aperture to aperture of the same magnet. Experimental data (converted in the corresponding sigmas) are given in Table 4, second column. We then evaluate the sigma of the apertures of all magnets (Table 4, third column). The

[1)] One observes an additional increase in the prestress of the order of 5 MPa in the assembled cold mass, due to interference between the collars and the yoke; this effect disappears at 1.9 K, where the yoke is not affecting any more the azimuthal prestress.

Table 4: Standard deviations of the odd multipoles (collared coils, room temperature): measured values of the sigma between apertures of the same magnet, of the sigma between apertures of different magnets and its post-processing (A and B), and target values. A: experimental sigma between apertures of different magnets, assuming nominal shims. B: experimental sigma between apertures of different magnets, assuming nominal shims and nominal prestress.

	Same magnets	Diff. magnets	A	B	Target
b_3	1.0	3.8	1.5	1.5	1.4
b_5	0.23	0.58	0.43	0.45	0.42
b_7	0.04	0.19	0.07	0.07	0.22
b_9	0.02	0.08	0.04	0.04	0.07
b_{11}	0.01	0.01	0.01	0.01	0.00

target values for the sigmas specified by the beam dynamics (Table 9901, see Ref. [10]) are given in the last column of Table 4. One observes that the variation between apertures of the same magnet is well below the target values (last column in Table 4). This means that apertures of the same magnets are extremely reproducible, beyond what is required by beam dynamics.

On the other hand, the variation of the multipoles among different magnets is higher than the targets. Indeed, one has more than a factor two for b_3 and nearly a factor 1.5 for b_5. This means that at this early stage of the production the variability from magnet to magnet is still not under control. We try to trace back the origin of this variability, and we find that a relevant part is due to shims whose thicknesses is different from the nominal one. If we extract from the experimental data the part relative to the non-nominal shims (see Table 3) according to our sensitivity estimates (see Appendix A), the resulting sigma is in agreement with the target values (Table 4, column A). In column B we extracted both the contribution due to non-nominal shims and the different deformations due to variations in the prestress: the result is very similar to column A. One concludes that the sigma of the multipoles is mainly due to the different shim size, and not to differences in prestress.

2.1.3 Summarizing

In the four analysed prototypes, average b_3 and b_5 feature discrepancies with respect to the nominal design (more than 0.5 units), and the random part of b_3 and b_5 is larger than target values (up to a factor three). Indeed, if the contributions of non-nominal shims, collar deformation, and collar magnetic permeability are taken into account, the agreement of the average multipoles is recovered. We also found that the out-of-target random part of the low-order odd multipoles is due to non-nominal shims used for optimizing the prestress, in view of trying to achieve a better training performance. The discrepancies in the systematic component with respect to the nominal design of b_3 and b_5 are of -2.7 units and +1.5 units respectively.

The coil cross-section was optimized for the previous collar design, and aimed at a correction of persistent currents of 50% for the b_3 and 80% for the b_5 [1]. This is not consistent with the beam dynamics requirements [11, 12], that aim at a b_3 as low as possible

Table 5: Effect of an additional shim of 0.1 mm on odd multipoles at 300 and 1.9 K

	Inner		Outer	
	300 K	1.9 K	300 K	1.9 K
b_3	1.7	1.8	1.2	1.3
b_5	-0.25	-0.28	0.01	-0.02
b_7	0.12	0.12	-0.03	-0.03
b_9	0.05	0.05	0.00	0.00
b_{11}	0.00	0.00	0.00	0.00

at high energy, and therefore a geometric b_3 of zero. Therefore, the discrepancies in the systematic component of b_3 with respect to the optimal design is around +4 units. For b_5, a lower correction could be envisaged (50% only [12]), thus reducing the discrepancy to one positive unit.

This estimate provides the order of magnitude needed for re-tuning b_3 and b_5. More refined estimates of the needed correction should be worked out, taking into account the iron yoke effect, warm-to-cold correlations, a design change of the internal shape of the collars used in the preseries to partially compensate collar deformation [13], and the revised estimates of the persistent current contributions [14].

In the following we analyse the possibility of performing a re-tuning of these low-order multipoles by means of small variations of the nominal design.

2.2 Fine tuning of sextupole and decapole

2.2.1 Variation of shims

A variation of the allowed multipoles (mainly b_3 and b_5) can be obtained by varying the azimuthal coil length. This can be easily tuned during the production by changing the shim thickness (two free parameters: inner and outer layer). Indeed, if the coil and the collar dimensions are within the specifications, a shim variation also produces a change of prestress, and therefore of deformation. At room temperature, a 0.1 mm change in the shim size produces an additional prestress of around 12 MPa [15]. At 1.9 K this variation becomes 7 MPa (see Ref. [6]). The admissible window for the prestress is now fixed at 75 ± 15 MPa at room temperature; therefore the range of the allowed variation of the shim size is 0.12 mm. The impact on the multipoles is given in Table 5, where the contribution of a 0.1 mm variation of coil length (Appendix A) is added to the effect of an additional deformation (Appendix B) of 6 MPa at 300 K (first column) or of 3 MPa at 1.9 K (second column). Numerical data show that the maximum range of variation of the odd multipoles is 3.5 units of b_3, 0.4 units of b_5, and 0.17 of b_7. This is not sufficient for re-tuning b_3 and b_5 on the target values, the case of b_5 being more difficult.

2.2.2 Variations of coil cross section

For obtaining a wider possibility of changing the multipolar content, one should vary the lay-out of the blocks and of the copper wedges. We restrict ourselves to analyse copper wedge variations that preserve the shape of the coil, thus avoiding a change of the collars and of the tooling relative to the coil production. However, modification of the copper wedges implies also a change of the spacers at the head of the coil. Such a change can be managed with the existing design and manufacturing procedures within a 3 months time span [16].

In the present design, the inner layer is composed of four blocks separated by three copper wedges (see Figure 2), parametrized by the four azimuthal angles φ_3, φ_4, φ_5, φ_6, and by the four inclination angles α_3, α_4, α_5, α_6. Blocks 3 and block 6 are fixed by the midplane and by the collar pole respectively, and one is left with four degrees of freedom: φ_4, φ_5, and α_4, α_5. The outer layer features two blocks and one copper wedge and therefore a change of the copper wedge without affecting the coil shape is not possible. In the previous 5 block design two degrees of freedom only would have been available.

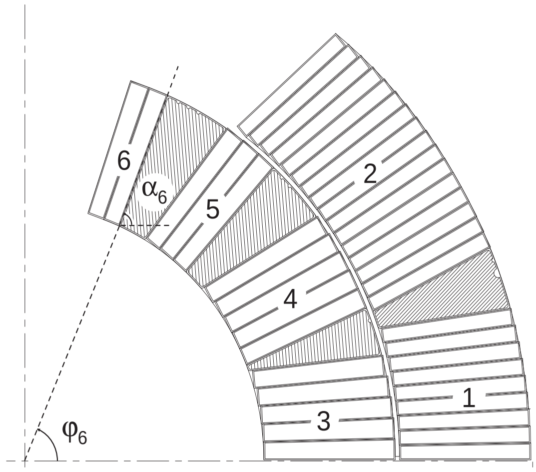

Figure 2: Cross-section of the LHC dipole coil, magnified view of the blocks

The mechanical constraints on the allowed variations of the angles φ_4 and φ_5 are rather loose: one only has to avoid that the copper wedge minimum thickness is smaller than 0.5 mm, because of the manufacturing process [13]. This limits the negative variations of φ_4 to 7 mrad. Positive variations of φ_4 and both negative and positive variations of φ_5 are allowed up to more than 35 mrad (i.e., 1 mm on the internal edge), that is far beyond what is needed to tune field quality. The inclination angles α_4 and α_5 should not differ too much from the corresponding positioning angles φ_4 and φ_5, to avoid a large tilt of the conductor with respect to the radial direction. This difference should not exceed 100-200 mrad (i.e., 5 to 10 degrees), also in this case enough for our purposes.

The effect of a slight change in the positioning of blocks 4 and 5 was analysed using a magnetic model where the geometric part only is considered. We assume that other effects like iron saturation and persistent currents can be added independently. In Table 6 we summarize the results: we considered a variation of φ_i that produces a shift in the block of $\Delta l = r\Delta\varphi_i = 0.1$ mm, where $r = 28$ mm is the inner coil radius. We also considered a variation of the tilt angles α_i that produces a shift in the middle of the block of $\Delta l = r_c\Delta\alpha_i/2 = 0.1$ mm, where $r_c = 15.4$ mm is the conductor width.

One can observe that the effect of a change in α_4 or φ_4 on b_3 and b_5 is rather similar; the same happens for α_5 or φ_5. Indeed, a variation of α has a smaller impact on b_7. This sensitivity table shows that changes of the order of a few tenths of mm in the positions of blocks 4 and 5 (without any collar modification) allow to re-center b_3 and b_5 on the optimal values for beam dynamics.

Table 6: Effect of a variation of 0.1 mm in the position of blocks 4 and 5 on multipolar errors

	Δb_3	Δb_5	Δb_7
$\delta\varphi_4$	-3.3	-0.50	+0.32
$\delta\alpha_4$	-2.5	-0.43	+0.14
$\delta\varphi_5$	-0.7	+0.88	-0.09
$\delta\alpha_5$	-0.7	+0.54	-0.01

3 Fine tuning of even multipoles

The two-in-one design of the LHC collars significantly breaks the left-right symmetry in each of the apertures, and leads to non-zero even multipoles. A relevant multipolar content of b_2 and b_4 naturally arises in a non-optimized design, and must be corrected to recover the nominal field quality. Higher order even multipoles are negligible due to the relatively high distance between the centre of the aperture and the outer radius of the collar (around 100 mm). The correction has to be carried out through a careful shaping of the iron yoke and of the ferromagnetic insert that transmits the forces between the yoke and the collars [4].

3.1 Warm measurements of assembled cold masses

In Table 7 we give the warm magnetic measurements carried out on the assembled cold masses of the first three final prototypes: MBP2N2, MBP2O1 and MBP2A2. Averages along the straight part are given in the usual units of 10^{-4} at a reference radius of 17 mm. Magnetic measurements are taken at low current (12 A) and 300 K averaging for positive and negative current flow. In the case of MBP2A2, that features sections different from the nominal one, the average is carried out along the nominal part only.

Table 7: Even field-shape harmonics measured at room temperature of the first three prototypes, assembled cold masses

	MBP2N2		MBP2O1		MBP2A2	
	Ap. 1	Ap. 2	Ap. 1	Ap. 2	Ap. 1	Ap. 2
b_2	4.04	-3.73	3.83	-4.78	4.78	-5.15
b_4	-0.40	0.40	-0.26	0.14	-0.21	0.53
b_6	-0.07	0.02	-0.02	-0.01	-0.02	-0.01

In this case, the average of apertures 1 and 2 is taken changing the sign of aperture 2. Averages and sigmas of the average multipoles in the three prototypes are given in Table 8, together with the nominal values and the targets for the sigma. One observes a relevant average b_2 (around 5 units), and a non negligible average b_4. On the other hand, the sigmas are below the target values. Therefore, solutions to optimize the average b_2 and b_4 have been analysed.

Table 8: Averages and sigma of even multipoles in the first three prototypes (assembled cold mass, room temperature) versus nominal and target values

	Average		Sigma	
	Measur.	Nomin.	Measur.	Target
b_2	4.39	0	0.54	0.68
b_4	-0.32	0	0.11	0.49
b_6	-0.02	0	0.02	0.09

3.2 Insert modifications to optimize even multipoles

The ferromagnetic insert (see Figure 3) has a relevant influence on the low-order even multipoles, and small modifications of its design can optimize them. At injection the magnetic field in the insert is of the order of some tenths of Tesla and therefore the iron is not saturated: field lines are perpendicular to the insert contours B-C-D and B'-C'-D' (see Figure 3) that face the collars. For this reason neither the dimension of holes H and H' inside the insert nor the shape of the upper part E-F and E'-F', in contact with the iron yoke, have relevant influence on field quality at injection.

3.2.1 Constraints to insert optimization

The insert is used to make it possible to assemble the iron yoke around the collars and to transmit via the yoke to the collars the forces generated by the shrinking cylinder so as to stiffen the dipole structure and minimize displacements. The force is transmitted from the yoke on the insert through the contact E'-F'-F-E and from the insert to the collars through the contact B'-A'-A-B. The elliptic parts of the collars C-D and C'-D' receive negligible forces and therefore are free for magnetic field optimization. The length of the contact E'-F'-F-E is not critical, and can be safely reduced around the ends E' and E up to at least 20 mm without affecting the mechanical role of the insert. A severe constraint is the length of the contacts B-C and B'-C': at least 4 mm are required to ensure a good positioning of the insert inside the collars during the assembly [13]. In the present design this length is 8.2 mm.

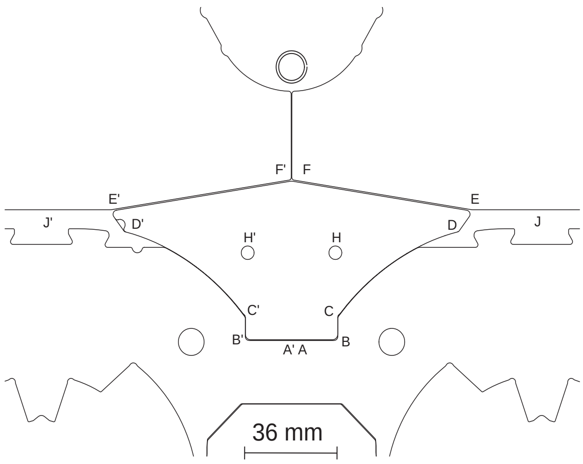

Figure 3: Insert geometry with collars and yoke

Modification of the insert geometry to optimize field quality mainly involves material removal. The additional empty volume created by these modifications will be filled with liquid helium, and if these volumes are relevant one could use fillers to reduce its quantity. Fillers between the upper part of the collar and the yoke (points J and J' in Figure 3) are already foreseen: relevant cuts in points D-E and D'-E' could be filled by simply modifying the existing fillers.

The 5.8 mm thick inserts are manufactured by fine blanking. Sharp edges have to be rounded with curvature radii of the order of 2 mm, due to fine blanking constraints.

3.3 Analysed modifications of the insert

We selected three regions of the insert contour in contact with the collars to act on the lower order normal multipoles (see Figure 4).

- A triangular cut at 45 degrees on the lower corner of the insert.
- A semihole of 8 mm radius in the mid part of the elliptic contour of the insert.
- An 18 mm cut of the toe of the insert.

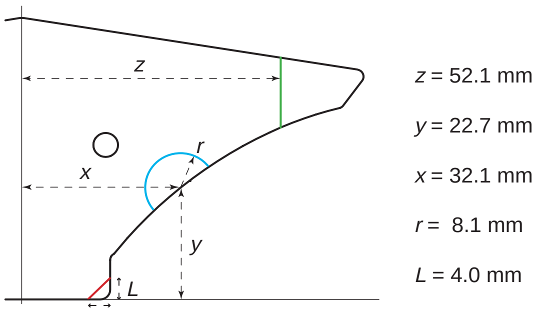

Figure 4: Insert geometry modifications tested on prototypes

These solutions have been worked out using a numerical code [8], to find ways of acting independently on b_2 and b_4 without affecting too much b_3. Results (see Table 9) show that the triangular and the circular cut have similar effects (1.5 units in b_2 and no impact on higher orders). On the other hand, the cut of the insert toe is the only way of acting also on b_4. Three sections with inserts featuring the above modifications have been built and assembled in the prototype MBP2A2 to test the validity of our magnetostatic code. Results are given in Table 9 , where a confidence level of 95 % (two sigma) has been considered for the experimental measurements. The agreement between simulations and experiments is excellent.

The impact of these modifications on the multipoles at higher fields has been checked. Iron saturation starts to be relevant at a current of 5000 A. In all cases the variation in the quadrupole is below two units, i.e. the same order of magnitude as in the nominal design [17, 18].

3.4 Proposed modifications of the insert

The version of the insert used for the first pre-series magnets has been chosen to reduce the even multipoles as much as possible. One has to correct four units of b_2 and -0.3 units of b_4. Among the different possibilities offered by the tested insert modifications, it has been decided not to modify the lower part (triangular cut). Therefore, both the semicircular hole and removing of part of the insert toe has been used. A smaller cut of the toe (14 mm instead of 18 mm, see Fig. 5) has been implemented to avoid an overcorrection of both multipoles. According to the experimental measurements, this insert modification

Table 9: Sensitivity on insert modifications, computed versus measured values

	Δb_2	Δb_3	Δb_4
Triangle Comp.	1.22	-0.33	0.04
Triangle Meas.	1.15 ± 0.30	-0.25 ± 0.16	0.00 ± 0.06
Circle Comp.	1.56	-0.16	-0.04
Circle Meas.	1.84 ± 0.24	-0.23 ± 0.14	-0.06 ± 0.14
Cut Comp.	3.43	0.83	-0.29
Cut Meas.	3.09 ± 0.26	0.66 ± 0.14	-0.29 ± 0.06

should provide a correction of 3.9 units of b_2 and -0.26 units of b_4. A test of this solution on the last prototype is in progress.

Some concern has been expressed about the impact of these modifications on b_3; the proposed new design increases b_3 by less than 0.5 units, according both to the measurements and to the simulations shown in Table 9. This effect is small when compared to the reproducibility of this multipole (one observes variations of 1 to 2 units between apertures of the same magnet, see Table 1). Moreover, the target for the sigma of b_3 is 1.5 units, i.e. three times larger then the variation induced by insert modifications. This additional effect of less than 0.5 units is also much smaller than the observed discrepancies with respect the nominal design (around 3 units).

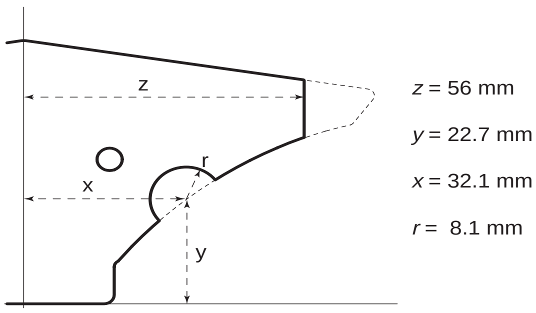

Figure 5: Insert geometry chosen for the series

4 First estimates of uncertainty

Beam dynamics simulations are based on the assumption that one has eight production lines; each line produces magnets whose multipoles have a Gaussian distribution with the same sigma, and different averages. The standard deviation of these averages is called the uncertainty. At this very early stage of the production, variations in magnet field quality between the producers lie in the different shim thicknesses used in the collared coil. This may be due to variation in the azimuthal coil length of the cured coils, depending on the tooling. The shims thickness that has been used in the last collared coils built in the three firms (the first magnet of the pre-series for Ansaldo and Noell, and the third one for Alstom) are given in Table 10.

To work out the impact of these variations on field quality, we have to use the sensitivity estimates shown in Appendix A, since different shims are used to aim at the

Table 10: Shim sizes used for the first Ansaldo and Noell pre-series magnet, and for the third Alstom, and impact on low-order odd multipoles

	Shims [mm] Inner	Outer	Δb_3	Δb_5	Δb_7
Alstom	0.35	0.95	5.0	-0.60	0.17
Ansaldo	0.25	0.90	2.3	-0.23	0.05
Noell	0.15	0.97	1.4	0.09	-0.10
Estimated uncertainty (sigma)			1.9	0.35	0.13
Target uncertainty (sigma)			0.9	0.42	0.00

same nominal prestress. We therefore obtain the expected variations in the odd normal multipoles of the collared coils between the three producers. A comparison with the target value (last two rows of Table 10) shows that if these shims thicknesses were kept along the production, the uncertainty for b_3 would be two times larger than the target. This is an optimistic estimate, since all the other effects are neglected.

To reduce the uncertainty due to shim size below the target values, the shims thickness variation among different firms should not exceed 0.03 mm. A uniformization of the shim thicknesses to the same average value would allow to reduce the uncertainty below the target value, within the prestress constraints.

5 Intrinsic limits to the production control

In this last section we give an estimate of the intrinsic limits to the control of the normal multipoles during the manufacturing. These limits are due to a variability of the field quality in the dipoles that we do not manage to modelize in a deterministic way, and that therefore we cannot control. An estimate of these limits is a relevant topic for understanding up to which precision the cross-section design and optimization should be carried out. Moreover, they provide the most optimistic estimate of what we can expect from the production control. A check of the consistency of these limits with the target values for the beam dynamics is also necessary to verify the feasability of the machine.

A first estimate of these intrinsic limits in the field quality control is based on the approach described in Ref. [19, 5]. Due to mechanical tolerances, conductors will never be exactly in the nominal design positions. The effect of these imperfections on the multipole components can be estimated: assuming that conductors are randomly placed around their nominal positions with an r.m.s. displacement of 0.025 mm, we obtain the corresponding distribution of random multipolar components whose sigma is given in Table 11, second column. These values agree to the measured variations of the multipoles along the longitudinal axis of the magnet (see Ref. [5]).

A second estimate of the lower bound to the control of field harmonics can be given by the variation of the multipoles from aperture to aperture of the same magnet. This is an experimental measurement of our capability of reproducing the same field harmonics in optimal conditions (same tooling, same manufacturer, same collaring). The sigma of the multipole distribution corresponding to the measured variations from aperture to aperture are given in Table 11, third column.

These two estimates are not very different, the first one being somewhat more

Table 11: Estimate of the intrinsic limits to multipole control during production and target values, in sigma of the corresponding Gaussian distribution

	Limits		Target	
	Simulations	Exp. Data	Sigma	Uncertainty
b_2	0.71	0.5	0.68	0.85
b_3	0.43	1.0	1.45	0.87
b_4	0.26	0.06	0.49	0.34
b_5	0.15	0.23	0.42	0.42
b_7	0.05	0.05	0.22	0.00
b_9	0.02	0.02	0.07	0.00
b_{11}	0.01	0.01	0.00	0.00

optimistic for the odd multipoles and pessimistic for the even ones. One can conclude that in a single magnet, the intrinsic limit in the control of the multipoles is around 0.5 units of b_2, up to 1 unit of b_3, 0.1 units of b_4 and 0.2 units of b_5 (one sigma). This is also the best agreement that we can expect between our model and measurements of a single magnet. In principle, the control over the average of a set of N magnets can be carried out with a higher precision, since one gains a factor $\sqrt{N}$.

The target values for beam dynamics are also given in Table 11: in column 4 we give the target sigma for a single production line, and in column 5 we give the sigma of the averages between different production lines (i.e, the uncertainty). A comparison with column 2 and 3 of the same Table shows that the estimated intrinsic limits to production control (both from simulations and experimental data) are not in conflict with the beam dynamics requirements.

6 Conclusions

We have analysed the field quality at room temperature of the first four final LHC dipole prototypes. The aim of this work is to give a preliminary assessement of the agreement of the field shape with the nominal design and with the target values, and to outline possible correction strategies that minimize the impact on the time schedule and costs.

The collared coil data of four prototypes have been analysed. The average odd multipoles feature a discrepancy of -3 units of b_3 and of +1.5 units in b_5. This is mainly due to two effects: the deformation of the collars due to the azimuthal prestress, and the magnetic permeability of the collars. When these effects are taken into account, one recovers a good agreement between design and measurements.

We point out that the nominal design is not consistent with the beam dynamics requirements: the coil cross-section aims at a relevant correction of b_3 persistent currents at injection, whilst beam dynamics considerations require no correction at all. This decreases the optimal value of b_3 by around 7 units, bringing the discrepancy from -3 units to +4 units.

The standard deviation of the odd multipoles is larger than the targets. This is mainly due to the use of different shim sizes to optimize the prestress in the coil. If this effect is taken out using the current estimates, the standard deviation of odd multipoles agrees with the targets.

We explore two possibile strategies to perform a tuning of b_3 and b_5 during the production. A change in the shim size allows to act in a very simple way on b_3 up to ± 3 units and on b_5 up to ± 0.3 units. A larger re-tuning of b_5, as it is suggested by experimental data, would require a change in the coil cross-section. We outline a strategy that allows to change two copper wedges in the internal layer without changing the collar shape, thus minimizing the impact on production.

The assembled cold mass data of three prototypes have been analysed to work out estimates on even normal multipoles. A relevant value of b_2 (5 units) has been found. On the other hand, the standard deviations of even multipoles are well below the targets. We have worked out three modifications of the ferromagnetic insert between the collars and the iron yoke to optimize b_2 and b_4. These solutions have been tested on a prototype, finding a good agreement with simulations. We then have proposed a new design of the insert to minimize both b_2 and b_4, that will be used for the pre-series production.

We have given a first estimate of the uncertainty, based on the assumption that it is due to different shim thicknesses used by the three producers. If the foreseen values will be used for all the production, the uncertainty in b_3 will be three times larger than the target. This could have a relevant impact on the recently foreseen installation scenarios [20].

We have worked out an estimate of the intrinsic limits that one has on the control of field harmonics on a single magnet, both for the design and optimization phase, and during the production. These limits are consistent with the target values of the random components.

Acknowledgements

We wish to acknowledge P. Fessia, M. Modena, D. Perini, A. Russo, G. Spigo, D. Tommasini and T. Verbeeck for discussing with us the mechanical constraints in the magnet design and the material properties. A special thank to F. Savary that has made possible the assembly of MBP2A2 with variable inserts, used for the even multipole optimization. We wish to acknowledge S. Russenschuck and C. Voellinger for help and discussions on the field computations and optimizations using ROXIE. We thank O. Brüning, S. Fartoukh, J. P. Koutchouk, F. Ruggiero, F. Schmidt and L. Walckiers for discussing with us the target values of the field harmonics. We finally wish to thank C. Wyss for stimulating and supporting this work, and for his remarks and suggestions.

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A Sensitivity on azimuthal cavity size

We consider a coil compression that leads to a larger cavity azimuthal size of $\Delta l =$ 0.1 mm (measured from the midplane to the pole). The effect of this change on the multipoles can be first modelled by assuming that the coil uniformly shrinks in the azimuthal coordinate [model 1, see Table 12]. However, copper wedges are much harder than the coil: their Young modulus is around 100 GPa, whilst the coil features a pressure-dependent Young modulus of the order of 10 GPa at 60 MPa. Therefore, we considered a second approximation where copper wedges are incompressible and all the shrinkage in the azimuthal size is due to a compression of the blocks [model 2, Table 12]. Moreover, we considered a finite element model of the magnet cross section and we simulated the effect of a shim whose size is 0.1 mm larger, *but keeping the same prestress* (i.e., the same collar deformation) by reducing the unloaded coil length of 0.1 mm [model 3, Table 12]. The results of the model 2 and 3 are very similar, and agree with previous estimates given in Ref. [21].

Table 12: Effect of a 0.1 mm larger azimuthal cavity size on odd multipolar errors, estimates through numerical models

	Inner coil		
	Δb_3	Δb_5	Δb_7
Model 1	+1.3	-0.41	+0.15
Model 2	+1.8	-0.33	+0.13
Model 3	+1.9	-0.32	+0.13
	Outer coil		
	Δb_3	Δb_5	Δb_7
Model 1	+1.4	-0.06	-0.02
Model 2	+1.5	-0.07	-0.02
Model 3	+1.4	-0.06	-0.02

B Sensitivity on deformations

The effect of collar deformations on field quality has been evaluated using a finite element code [7] for the structural analysis, and a magnetostatic code [8] for the multipole evaluation. The finite element model and its properties are described in Ref. [6]. Here, we use the model to work out the effect of a given azimuthal prestress on the multipoles, *keeping constant the geometry of the unloaded cavity.* Prestress at 300 K is around 75 MPa, and at 1.9 K is around 30 MPa. Therefore the effect of collar deformation is expected to be much more visible at room temperature. In Table 13 we give the impact on odd multipoles of the collar deformation as a function of the azimuthal prestress of the coils. One can see that the effect of deformations is non-negligible mainly for b_3 and b_5. From b_9 onard the effect is less than 0.1 units. Explicit dependence around the working point of 70 MPa can be worked out through linearization:

$$\Delta b_3 = -0.98 - 0.0363\,\sigma \tag{1}$$

$$\Delta b_5 = 0.38 + 0.0112\,\sigma \tag{2}$$

$$\Delta b_7 = -0.07 - 0.0017\,\sigma \tag{3}$$

Table 13: Effect of a collar deformation due to an azimuthal prestress σ on odd multipoles

σ (MPa)	Δb_3	Δb_5	Δb_7
10	-1.0	0.37	-0.06
20	-1.6	0.56	-0.09
30	-2.0	0.70	-0.11
40	-2.4	0.83	-0.13
50	-2.8	0.95	-0.15
60	-3.2	1.07	-0.17
70	-3.5	1.17	-0.18
80	-3.9	1.28	-0.20
90	-4.2	1.37	-0.21

The sensitivity on the prestress is similar at 300 K and at 1.9 K, but at 1.9 K one has an additional offset in the multipoles due to the different thermal contraction coefficients of the collar and of the coil. Further analysis should be carried out, based both on finite element models and warm-to-cold correlations worked out by magnetic measurements.

C Sensitivity on collar permeability

The stainless steel used for the collars has a magnetic permeability that differs from one by a few units in 10^{-3}. Typically, μ is 1.002 to 1.003, and its value has small variations (of the order of 10^{-4}) when the external magnetic field ramps from 0.1 T to 8 T. The dependence of the shift induced in the multipoles on the magnetic permeability is linear; values are given in Table 14. Also in this case, the effect is non-negligible on b_3 and b_5.

Table 14: Effect of a non-zero collar permeability on odd multipoles

μ_c	Δb_3	Δb_5	Δb_7
1.0010	-0.6	0.17	-0.04
1.0015	-0.9	0.25	-0.06
1.0020	-1.3	0.34	-0.08
1.0025	-1.6	0.42	-0.10
1.0030	-2.0	0.51	-0.12
1.0035	-2.3	0.59	-0.14

D Examples of copper wedge modifications

We consider a modification of the coil cross-section in the position of the block 4, azimuthal position (variable ϕ) by 0.1 mm. This implies a change in the angle of $0.1/28/\pi*180 = 0.204$ degrees, i.e. 3.57 mrad. In the AUTOCAD^{TM} input file, this change in the variable ϕ corresponds to add a slice of 0.1 mm to the copper wedge between the third and the fourth block, and to remove the same slice from the copper wedge between the fourth and the fifth block. According to our sensitivity tables, the impact of this modifications on b_3, b_5 and b_7 is of -3.3, -0.50 and +0.32 units respectively.

As a second example, we consider a modification of the tilt angle α_4 by 0.15 mm. This implies a change in the angle of $0.15/7.7/\pi * 180 = 2.232$ degrees, i.e. 19.48 mrad. In the AUTOCAD^{TM} input file, one has to increase by 2.232 degrees the angle of the copper wedges between the third and the fourth block, and has to reduce the angle of the copper wedge between the fourth and the fifth block by the same amount. This modification should change b_3, b_5 and b_7 by -3.8, -0.63 and +0.20 units respectively.